

Potential contributions of forestry and wood use to climate change mitigation in Japan

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Abstract By considering trade-offs and complementarity between carbon removal from the atmosphere by forests and emission reduction by wood use, we developed a forest-sector carbon integrated model for Japan. We discuss mitigation measures for Japan based on model projections. The integrated model included the forest model and the wood use model. Based on three scenarios (baseline, moderate increase, and rapid increase) of harvesting and wood use, the integrated model projected mitigation effects including carbon removal by forests and emission reduction through the wider use of wood, until 2050. Results indicate that forests will not become a source of net carbon emissions under the three scenarios considered. The baseline scenario is most effective for mitigating climate change, for most periods. However, the sum total of carbon removal in forests and carbon emission reductions by wood use under the rapid increase scenario exceeded the one of the moderate increase scenario after 2043. This was because of strong mitigation activities: promoting replanting, using new high-yield varieties, and wood use. The results also indicated that increases in emission reduction due to greater wood use compensated for 67.9 % of the decrease of carbon removal in 2050, for the rapid increase scenario. The results show that carbon removal in

forests is most important in the short term because of the relative youth of the planted forests in Japan, and that mitigation effects by material and energy substitution may become greater over the longer term.

Keywords Carbon removal · Emission reductions · Forest sector · Integrated model · Model projection

Introduction

According to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC 2013), it is extremely likely that human activities have been the dominant causes of the warming observed since the mid-20th century, and that limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. Thus, actions for mitigating climate change are required in the forestry sector as well. There are two different approaches to mitigating climate change in the forestry sector. One is to increase carbon removal from the atmosphere by forests, and the other is to reduce emissions through the use of wood. The two approaches exhibit a trade-off relationship (e.g., Dufrêne et al. 2005; Lecocq et al. 2011; Seidl et al. 2007). For example, avoiding harvesting may increase carbon removal by forests, but may result in increased emissions because of reduced wood usage and substitution by fossil fuels. The IPCC's *Fourth Assessment Report* (2007) indicates that the design of a forest sector's mitigation portfolio should consider the trade-offs between the two approaches. On the other hand, Bellassen and Luyssaert (2014) discuss a complementary relationship between carbon removal in forests and the reduction of emissions through the wider use of wood, and show that the future trajectory of the carbon sink varies

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according to the state of sequestration and maturity of forests. Due to such tight trade-off and complementarity relationships, the overall potential of the forest sector to mitigate carbon emissions needs to be evaluated.

Climate change gradually progresses over several decades, and forests are managed in rotations of at least several decades. Therefore, the impacts of climate change and measures to counteract them in the forest sector should be developed on a long-term basis, ranging from several decades to more than one century. Projections are also required to assess the mitigation effects of scenarios in the forest sector. Moreover, this will allow backcasting to set future goals and examine which scenario should be followed to achieve these goals. Therefore, to examine the various possible scenarios in the forest sector, it is necessary to compare their effects on the basis of long-term projections.

Kallio et al. (2013) examined the trade-off between sequestered carbon in forests and the substitution of wood for fossil fuels in Finland. They simulated carbon balances from 2012 to 2035 and concluded that renewable energy targets of the EU were excessive and harmful to the climate. Perez-Garcia et al. (2005) concluded after life cycle assessment that wider use of forest products would lead to a significant reduction in atmospheric carbon by displacing more fossil fuel-intensive products in housing construction in the USA. Werner et al. (2005) reached a similar conclusion in the case of Switzerland. On the other hand, Lecocq et al. (2011) concluded that stock policy (payment for sequestration in situ) was the best in terms of mitigating carbon emissions for the period 2010–2020 in France. Smyth et al. (2014) quantified the biophysical climate change mitigation potential of Canada's forest sector. They simulated the carbon budget of the Canadian forest sector from 2012 to 2050 and concluded that a reduced harvest, along with efficient, long-term use of wood products, would be most effective in mitigating climate change. They also noted that there was a trade-off between the short-term and long-term effects of emission reductions. Ter-Mikaelian et al. (2015) concluded that a sustained yield does not necessarily mean a carbon-neutral outcome. They concluded that some forest biomass sources may provide near-immediate reductions in greenhouse gases, while others result in decades- to century-long increases in atmospheric greenhouse gases. Choosing or combining these two different forest-sector mitigation approaches (substitution and sequestration) is thus complex and requires further research.

The goals of this study were to develop a forest-sector carbon integrated model for Japan that incorporates forests, forestry, and wood use, and to compare the climate change mitigation effects of scenarios for forestry and wood use on the basis of projections from this model.

Materials and methods

Development of the forest sector carbon integrated model

Overall structure

To evaluate the two approaches for mitigation in the forest sector described above, we designed the overall structure of the integrated model to consist of two main components. The forest model component used environmental and geographical factors to estimate growth of the forest and carbon stock changes, and the wood use model component estimated the log volume used for each product, carbon stock changes in harvested wood products (HWP), and emission reductions through substitution (Fig. 1).

Projections of the integrated model were performed based on climate scenarios and policy scenarios for mitigation in the forest sector (Fig. 1). The climate scenarios produced temperature and precipitation based on the MIROC-hire model (K-I Model Developers 2004), and the forestry scenarios estimated harvesting area and timber production in the future. We used the national forest database developed by Matsumoto et al. (2007) as the basis of the initial forest resource information for the projections. All forest stands in Japan have been recorded and are managed using forest maps and registers (Hirata et al. 2010), and this information was integrated into the national forest database. We included forests on main islands including Hokkaido, Honshu, Shikoku, Kyushu, and Okinawa, but forests on other smaller islands were excluded from the projections. Thus the forest area was approximately 23.2 million ha for our projections. We reconstructed the 1-km resolution national forest database, where each 1-km grid cell contains information on species, age class, and area of each stand within the cell (Mitsuda et al. 2013). Multiple records for different species and age classes are stored in each 1-km grid. The stand structure of each stand, such as average tree size, tree number, and stocking biomass, was estimated using the National Forest Inventory (e.g., Kitahara et al. 2008, 2010a, b).

The main models and scenarios for forestry and wood use will be discussed in detail in the following subsections.

Forest model

We developed a simulation model, referred to as the “forest model” in this study, to describe carbon dynamics in a stand consisting of a carbon cycle-based stand-level plant growth model and a soil carbon model. The plant growth model developed here was a process-based model including physiological interactions between plants and

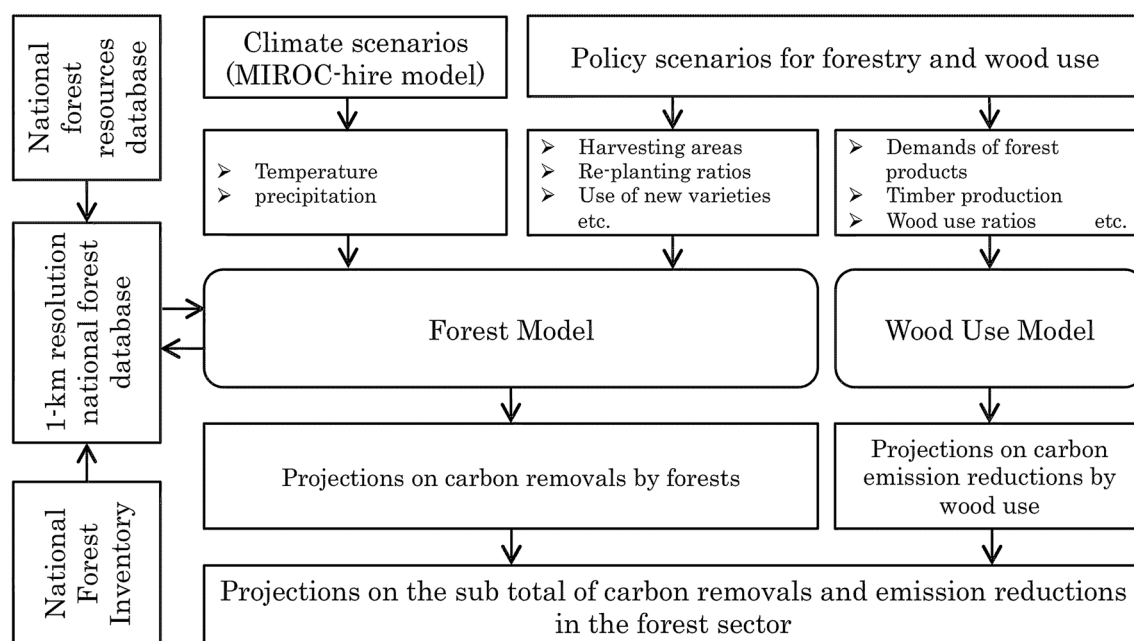


Fig. 1 Structural scheme of the forest sector carbon integrated model

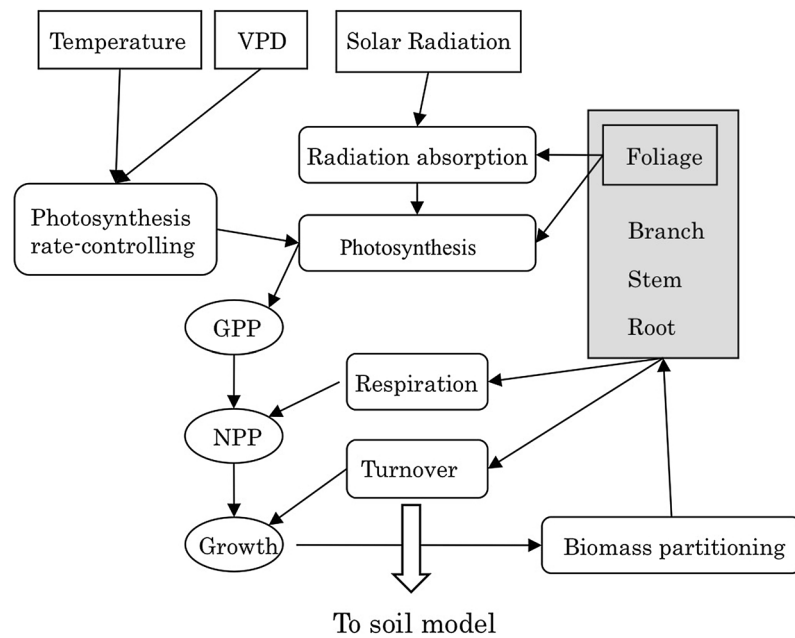
their environment. It is thus suitable for simulating the effects of various climatic condition and various management regimes (e.g., combinations of timing and intensity of thinning) on stand growth (e.g., Mäkipää et al. 1999; Mäkelä et al. 2000; Lasch et al. 2005).

A number of process-based forest growth models have been developed to understand and simulate the carbon cycles of forest ecosystems (e.g., Gertner et al. 1996; Landsberg and Waring 1997; Chiba 1998; Kurz and Apps 1999; Mäkelä et al. 2000; Dufrêne et al. 2005). We chose the 3-PG model developed by Landsberg and Waring (1997) as the basis of our plant growth model, because the simple model structure was suitable for applying to the large number of stands. The model structure was simple but robust and also reasonable because the essential ecological processes relating to stand growth were considered. Here, we only briefly explain the plant growth model because it was explained in detail in a previous paper (Mitsuda et al. 2013). We modified the 3-PG model to a simpler version that included only six processes: photosynthetically active radiation absorption, photosynthetic production, rate control of photosynthesis by environmental factors, respiration, turnover, and growth partitioning (Fig. 2). The time step of this model was monthly for calculating photosynthesis and respiration, and yearly for calculating turnover and growth partitioning. Dry matter weights per unit area for four living woody biomass pools (i.e., foliage, stems, branches, and roots) were used as the basis for calculating the carbon balance. For coniferous planting species including sugi (*Cryptomeria japonica*), hinoki (*Chamaecyparis obtusa*), karamatsu (*Larix kaempferi*), todomatsu

(*Abies sachalinensis*), and ezomatsu (*Picea jezonensis*), we treated a stand canopy structure as five leaf strata, and calculated the intensity of radiation, related photosynthetic rate, and gross primary production for each leaf stratum. By using this stand canopy structure with five leaf strata, we could evaluate the after effects of thinning. For other species, including akamatsu (*Pinus densiflora*) and kuro-matsu (*Pinus thunbergii*), as well as evergreen and deciduous broadleaf species, we used a single leaf layer canopy structure. The parameters of this model were estimated for the nine species groups above, using data from long-term repeated measurements at permanent plots located in the National Forest, and the National Forest Inventory data (Mitsuda et al. 2010).

Litter fall from plants calculated in the turnover process of this model as well as logging residuals derived from clear-cutting and thinning were treated as inputs for the soil carbon model. We applied the modified version of the Yasso model to simulate soil carbon dynamics in this study (Liski et al. 2005) because Yasso is one of the most widely used soil organic carbon models. The modified model consisted of six compartments (five litter compartments—leaves, branches, stems, fine roots and coarse roots; one soil humus compartment), and each compartment consisted of three sub-compartments with different decomposability attributes. The decomposition of the litter and soil compartment was described by first-order decay functions. The soil model was run at an annual time step, and the decay constants were controlled by the annual mean temperature and annual precipitation. As often pointed out, the spin-up run for thousands of years with the current litter fall input

Fig. 2 Outline of the carbon cycle-based stand-level plant growth model in the forest model



revised Mitsuda et al., 2013

does not reproduce the current soil carbon stock because of past forest conditions and land use. Hence, we relaxed (adjusted) the equilibrium soil carbon stock calculated through the spin-up run to match the soil carbon stock at the initial stage with observed soil carbon stock (Wutzler and Reichstein 2007; Carvalhais et al. 2008; Hashimoto et al. 2011). The compartments were initialized by running the model for 3000 years using modeled litter fall in 2010. They were scaled using data from the National Forest Soil Carbon Inventory (Ugawa et al. 2012).

We applied the stand-level plant growth model and soil carbon model to each stand in the 1-km resolution forest database, using climatic values provided from climate scenarios derived from MIROC-hire (Fig. 1). Some stands, randomly selected according to their suitability for forest operations (evaluated by road density and topography), were thinned or harvested to produce the timber volume planned in the scenarios. The thinning regime was constant: 30 % less thinning. Some of the harvested stands were replanted with the replanting ratio determined in the scenarios. Thus, we projected carbon stocks and flows in all forest stands, including the soil, in Japan until 2050.

Wood use model

The wood use model is outlined in Fig. 3 and was formulated using the following two factors. The first factor was wood flow from roundwood production (obtained from the above-mentioned forest model) to sawnwood, plywood and chip production, final use of wood products for

building construction (sawnwood and plywood), civil engineering (roundwood and sawnwood), furniture (sawnwood and plywood), and paper (chips). Energy uses of logging residue (obtained from the forest model), processing residue (generated from sawnwood and plywood production from roundwood and residue generated during building construction and furniture production), and waste wood (from demolished buildings, civil engineering structures, and furniture) accompanied the wood flow (Kayo et al. 2014). The volume of wood yielded by a given volume of roundwood was set to 0.637 for sawnwood and 0.618 for plywood (Ministry of Agriculture, Forestry and Fisheries 1991–2014).

The second factor was the wood stock used in building construction (wooden and non-wooden buildings), civil engineering (log piles and wooden guardrails), furniture and paper. The wood stock was calculated using the wood flow and the lifetime function that determines the decay rate of wood products (Tsunetsugu and Tonosaki 2010). We assumed 35 years for the wooden building half-life, 30 years for non-wooden buildings (Tsunetsugu and Tonosaki 2010), perpetuity for log piles (Kayo et al. 2011), 10 years for wooden guardrails (Noda et al. 2016), 20 years for furniture, and 2 years for paper (Kayo et al. 2014). The respective lifetime functions were obtained from Kayo et al. (2015). The earliest wood stock calculated was for 1970.

The wood use model also evaluated three carbon emission reduction effects based on the carbon balance of the wood flow and stock. The carbon stock effect (annual change in carbon stock in wood derived from domestic forests) was

The flowchart illustrates the Forest Model's components and their interactions. It starts with the **Forest Model** (hexagon) leading to **Roundwood production** (rectangle). **Roundwood production** feeds into **Sawnwood/plywood/paper production** (rectangle) and **Energy use** (rectangle). **Roundwood/chip/woodpulp imports** (rectangle) also feeds into **Sawnwood/plywood/paper production**. **Sawnwood/plywood/paper production** feeds into **Wood products use (building, civil engineering, furniture, paper)** (rectangle) and **Energy use**. **Wood products imports (sawnwood, plywood, furniture, paper)** (rectangle) also feeds into **Wood products use**. **Wood products use** feeds into **Wood products stock (building, civil engineering, furniture, paper)** (rectangle) and **Energy use**. **Scenarios of energy use** (rectangle) also feeds into **Energy use**. **Energy use** feeds into **Energy substitution** (cloud). **Material substitution** (cloud) and **Scenarios of wood use** (rectangle) also feed into **Energy substitution**. **Carbon stock** (cloud) is also shown. A legend at the bottom defines the symbols: hexagon for Forest Model, rectangle with a double arrow for Future scenarios, rectangle with a single arrow for Wood flow and stock, and cloud for Emission reduction effect.

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graph TD
    FM{{Forest Model}} --> RP[Roundwood production]
    RP --> SPP[Sawnwood/plywood/paper production]
    RP --> EU[Energy use]
    RCI[Roundwood/chip/woodpulp imports] --> SPP
    SPP --> WPU[Wood products use]
    SPP --> EU
    WPI[Wood products imports] --> WPU
    WPU --> WPS[Wood products stock]
    WPU --> EU
    SES[Scenarios of energy use] --> EU
    EU --> ES((Energy substitution))
    MS((Material substitution)) --> ES
    SWUS[Scenarios of wood use] --> ES
    CS((Carbon stock))
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Legend:

- Forest Model
- Future scenarios
- Wood flow and stock
- Emission reduction effect

In the wood use model, statistical data were used for the period 1990–2013. Specifically, these data were derived from the Ministry of Agriculture, Forestry, and Fisheries (1991–2014) for wood flow from roundwood production to sawnwood, plywood, and chip production. The Ministry of Land, Infrastructure, Transport, and Tourism (1991–2014) data were used for final use in building construction, and data from the Interdisciplinary Committee on the Increased Use of Wood in Civil Engineering (2010) were used for final use in civil engineering. Data from the Ministry of Economy, Trade and Industry (1991–2014a) determined final use in furniture, and data from the Ministry of Economy, Trade, and Industry (1991–2014b) determined final use in paper. Three scenarios were assigned for the interval 2014–2050. The scenarios are explained in more detail in the following section.

In the baseline scenario, it was assumed that the area of the annual final harvest and replanting until 2050 would be almost constant in spite of the aging of planted forests from the planting boom generation in Japan. The average replanting ratios of planted forest to the areas of final harvest for 2005–2010 calculated for each prefecture were used as the constant replanting ratio (average 64 %). The initial national total ratio was 64 %. Genetic improvements were not considered. We considered tops, branches, and small trees as logging residue for clear-cut and thinning, and stumps were considered litter fall to the soil carbon pool. The proportion of wooden buildings and furniture made each year, and the volume of wood used in civil engineering projects all remain unchanged at the current level. It was assumed that the volume of paper use per person would remain unchanged at its 2013 level in 2014 and beyond. Paper consumption would change in line with future changes in population (National Institute of

Table 1 Carbon emission reduction intensities for material and energy substitution

Material or energy substitution	Unit	Value	References
Building construction: substitution of wooden buildings for non-wooden buildings	kg C/m ² (kg C/m ³)	60.6 (301.3 ^{a, b})	Japan Environmental Management Association for Industry (2014)
Civil engineering: substitution of wooden piles for cement and sand piles	kg C/m ³	46.8 ^a	Kayo et al. (2011)
Civil engineering: substitution of wooden guardrails for metal guardrails	kg C/m ³	64.5 ^a	Noda et al. (2016)
Furniture: substitution of wooden furniture for metal furniture	kg C/m ³	43.2 ^a	Japan Environmental Management Association for Industry (2014)
Energy: substitution of residues and waste wood for heavy oil	kg C/m ³	108.9	Japan Environmental Management Association for Industry (2014)

^a Emission reduction per volume of wood product stocked by the substitution

^b Calculated by dividing the intensity per area (60.6 kg C/m²) by the amount of wood product stored per unit area of wooden buildings (m³/m²) (Tsunetsugu and Tonosaki 2010)

Table 2 Indicators for the three scenarios

Scenarios	Forestry indicators			Wood use indicators		
	Timber production or final harvest area	Replanting ratio to final harvest area	New high-yielding varieties used	Building construction, furniture	Civil engineering	Energy use for heating
Baseline	Areas of final harvest, constant at recent level, 41,000 ha; timber production, 16 million m ³ in 2010	Constant at recent level, 64 %	None	Constant at present ratio of 35 %	Constant at recent level of 1 million m ³	Logging residue, 0 %; processing residue, 21 %; waste wood, 83 %
Moderate increase	Timber production, approximately doubled by 2050	Constant at recent level, 64 %	None	Increased to 50 % by 2050	Increased to 3 million m ³ by 2050	Logging residue, 0 %; processing residue, 24 %; waste wood, 87 %
Rapid increase	Annual timber production, 39 million m ³ in 2020 and 50 million m ³ in 2030–2050	Increased to 100 %	Increased to 70 % of annual planting by 2050	Increased to 70 % by 2050	Increased to 6 million m ³ by 2050	Logging residue, 49 %; processing residue, 27 %; waste wood, 90 %

Population and Social Security Research 2014). The current proportion of energy use from logging residue (0 %), processing residue (21 %), and waste wood (83 %) (Forestry Agency 2008; Ministry of the Environment 2013) would also remain at the same level until 2050, in the first scenario.

In the second (moderate increase) scenario, it was assumed that timber production would increase by 2050 with the increasing age of stands from the planting boom generation. The proportion of replanting areas after the final harvest was assumed constant at recently observed levels, and less than 100 % in each prefecture in Japan. The introduction of high-yielding varieties (improved seedlings

varieties for fast production) during replanting was also assumed to be moderate. Small but increasing areas of planted forests would be changed slowly to broad leaves forests after the final harvest. The volume of log production would also double from 2011 to 2050. The proportion of wooden buildings and furniture made each year would increase from the current level of 35–50 % by 2050. The volume of sawnwood and plywood input into the building and furniture sectors would increase with the increasing proportion of wooden buildings and furniture. The volume of roundwood and sawnwood used in civil engineering projects increases to 3 million m³/year by 2050 from the current 1 million m³/year. The volume of paper used was

assumed to be the same as in the baseline scenario. In addition to the current proportion of wood used for energy production, half of the unutilized processing residue and waste wood (24 % for processing residue and 87 % for waste wood) would also be used for energy production by 2050.

The third (rapid increase) scenario was based on ambitious forestry expansion in line with the Forest and Forestry Basic Plan of 2011, and the National Forest Plan for the period between April 2014 and March 2029. This scenario assumed a drastic increase in the utilization rates from thinning, together with substantial increases in final harvesting and areas of replanting. Log production would double to 39 million m³ by 2020, increasing to 50 million m³ by 2030, and stay at that level until 2050. Average areas of annual planting would more than double to 63,000 ha over the 15-year period; this would then stay constant until 2050. High-yielding varieties would be used for 70 % of replanting by 2050 in the third scenario. The proportion of wooden buildings and furniture made each year would increase to 70 % by 2050, and the volume of wood used in civil engineering projects would increase to 6 million m³/year by 2050. The volume of paper used was assumed to be the same as in the baseline scenario. In addition to the current proportion of wood used for energy production, half of the unutilized logging residue, and all of the unutilized processing residue and waste wood (49 % for logging residue, 27 % for processing residue, and 90 % for waste wood) would also be used for energy production by 2050.

Results

Carbon removal by forests

The simulated dynamics of carbon stocks of the total living woody biomass and soil pools in all the forests of Japan are shown in Fig. 4. Each line in Fig. 4 represents the dynamics of carbon stocks projected using one of the scenarios. In all three of the scenarios considered in this study, the carbon stocks of the entire forests of Japan continued to increase until 2050.

Figure 5 shows the projected changes in the carbon stock in total living woody biomass pools and soil pools in all the forests of Japan, with each line representing the annual carbon stock changes of a scenario. In the latest National Greenhouse Gas Inventory of Japan (GIO et al. 2014), the net carbon removal by forests, including in living biomass, dead wood, litter, and mineral soil, was reported to be 21.2 Mt C/year in 2012, while the value simulated in the baseline scenario was 21.9 Mt C/year. This indicates that the estimation of the current carbon

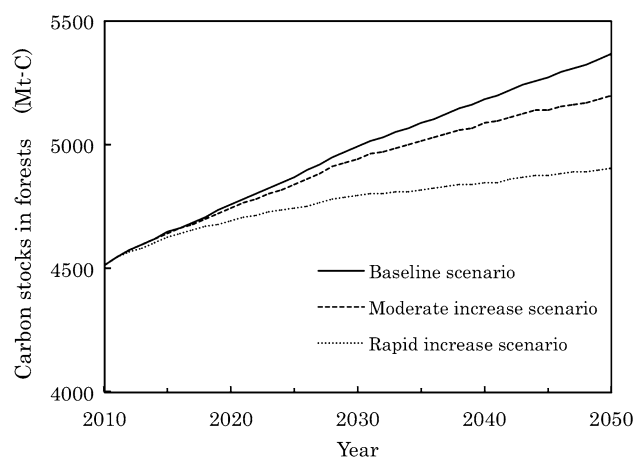


Fig. 4 Estimated carbon stocks in the living woody biomass pools and the soil pools in Japanese forests

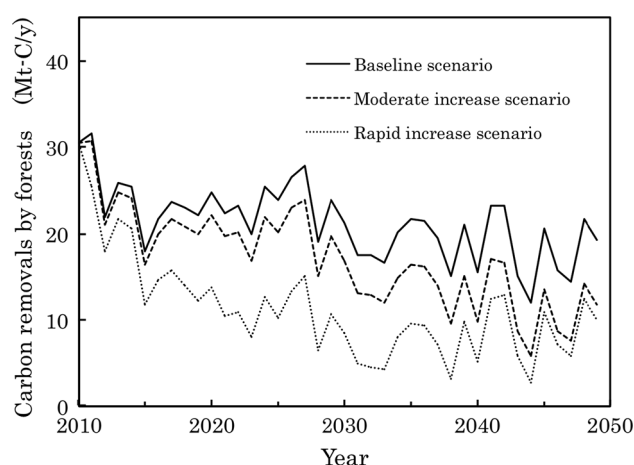


Fig. 5 Estimated changes in carbon stocks in the living woody biomass pools and the soil pools in Japanese forests

removal using the forest sector carbon integrated model almost coincides with that estimated by the government. In all scenarios, the change in carbon stock exhibited positive values, which indicated that the forests of Japan continue to be a net carbon sink until 2050. The annual rates of carbon removal were relatively large in the earlier simulation periods, but the rates rapidly decreased in all three scenarios. This rapid decrease in annual carbon removal by forests was mainly caused by a rapid decrease in the annual growth rate of the sugi planted forests, which occupied approximately 19 % of all the forested area of Japan. The majority of sugi planted forests are over 50 years old, so their annual growth rates should be decreasing. For the rapid increase scenario, the large harvests, especially in broadleaved forests, also caused a decrease in carbon removal by forests.

The carbon stocks in the living woody biomass pools were the highest under the baseline scenario, while the carbon stocks in the soil pools were the highest under the

moderate increase scenario. Mature forests contribute to a stable level of annual litter fall. Harvests contribute to increases in the temporary litter fall, but decrease the annual litter fall. Under the baseline scenario, the harvested amount was low; therefore, the annual litter fall level remained high and the temporary litter fall level was low. Due to the large areas of the stands felled to produce roundwood under the rapid increase scenario, the effects of decrease in the annual litter fall level were greater than the effects of increase in the temporary litter fall level.

Emission reductions by wood use

Under the baseline scenario, the carbon stock of HWP would not increase by 2050. On the other hand, in the scenarios in which wood use is promoted, the carbon stock effect was consistently seen up to and including 2050, rising to a maximum average of 2.2 Mt C/year between 2026 and 2030, in the rapid increase scenario.

Regarding the material substitution effect, under the rapid increase scenario, maximum average carbon emission reductions of 2.9 Mt C/year were obtained between 2046 and 2050. Breakdown by application shows 88 % derived from building construction, 8 % derived from civil engineering, and 4 % derived from furniture making. Therefore, the substitution of wooden building construction for non-wooden building construction could be expected to provide the largest reductions and become an effective mitigation strategy.

With respect to the energy substitution effect, under the rapid increase scenario, maximum average carbon emission reductions of 3.5 Mt C/year were obtained between 2046 and 2050, with 36 % derived from logging residue, 11 % from processing residue, and 53 % from waste wood. The latter was because of the high proportion of energy use for waste wood (see “[Scenarios for forestry and wood use](#)”).

Taken together, the carbon stock effect, the material substitution effect, and the energy substitution effect (Fig. 6), under the rapid increase scenario, could achieve a maximum average emission reductions effect of 7.6 Mt C/year between 2046 and 2050, which is equivalent to 2.1 % of Japan’s total carbon emissions in 2013 (Ministry of the Environment 2014).

Total evaluation of mitigation measures in the forest sector

Based on the three scenarios described above, projections for carbon removal and emission reductions were made up to 2050 using the forest sector integrated forestry carbon model. The results are shown in Fig. 7. To evaluate the mitigation effects of carbon removal and emission reductions under the trade-off and complementary relationship discussed earlier, we used the sum total of carbon removal in forests and carbon emission reductions by wood use.

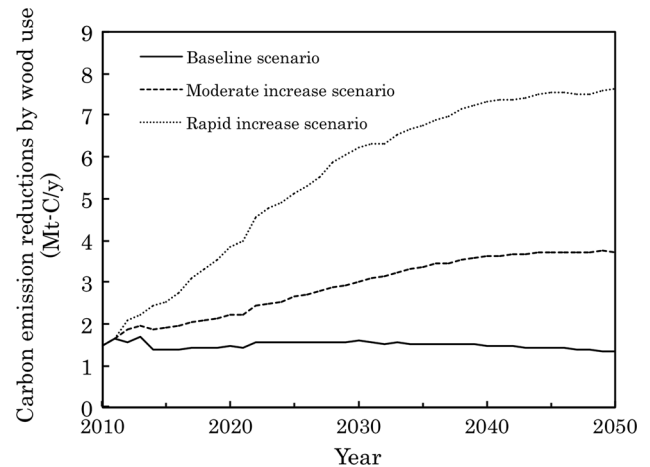


Fig. 6 Estimated carbon emission reductions through the use of wood including carbon stock changes and emission reductions through material substitution and energy substitution effects

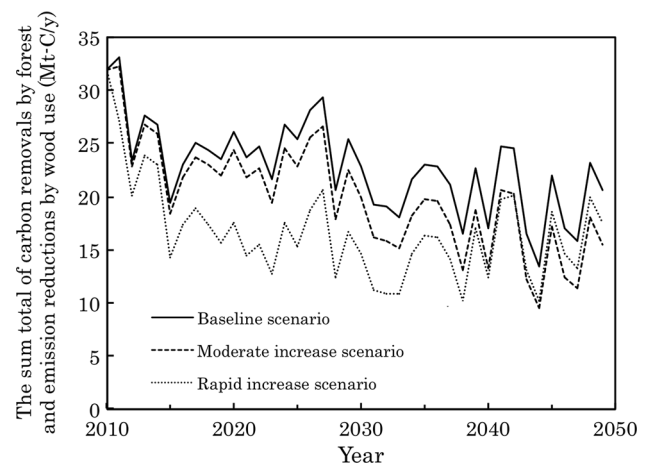


Fig. 7 Estimated mitigation effects in the forestry sector; the sum total of carbon removal by forests and emission reductions through the use of wood

As shown in Fig. 7, the sum total is the largest in the baseline scenario, followed by the moderate increase scenario, and then the rapid increase scenario, for most periods. The trend is the same as that for carbon removal in forests (Fig. 4). This shows that the effect of carbon removal is dominant in the forest sector. However, the differences among the scenarios become smaller over time, and the sum total for the rapid increase scenario is larger than the one for the moderate increase scenario after 2043. One reason for this is that strong mitigating activities, including 100 % replanting and using new high-yielding varieties in the rapid increase scenario, improve carbon removal in the long run. The other reason is that, while carbon removal by forests is lower under the rapid increase scenario, emission reductions by the expanded use of wood become greater, as shown in Fig. 6.

Fig. 8 A breakdown of the projected carbon removal and emission reductions

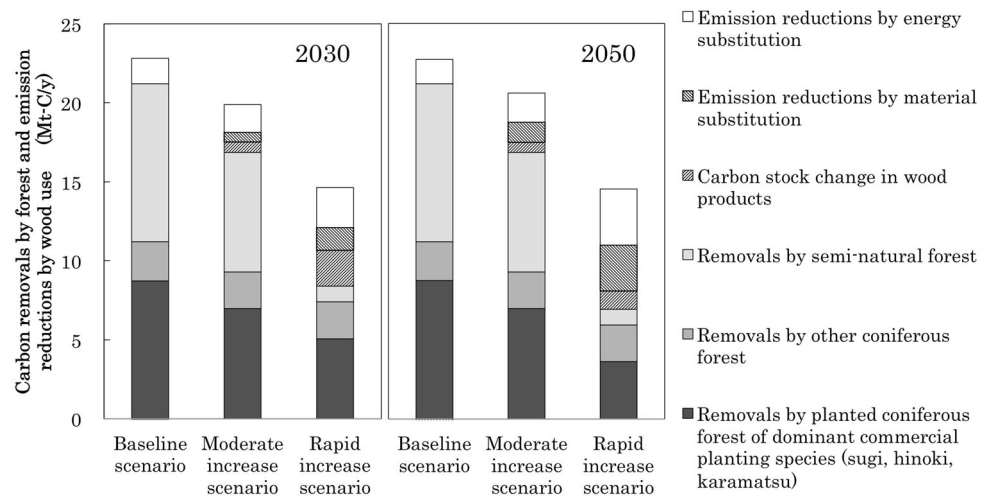


Fig. 9 Difference of the projected carbon removal and emission reductions from the baseline

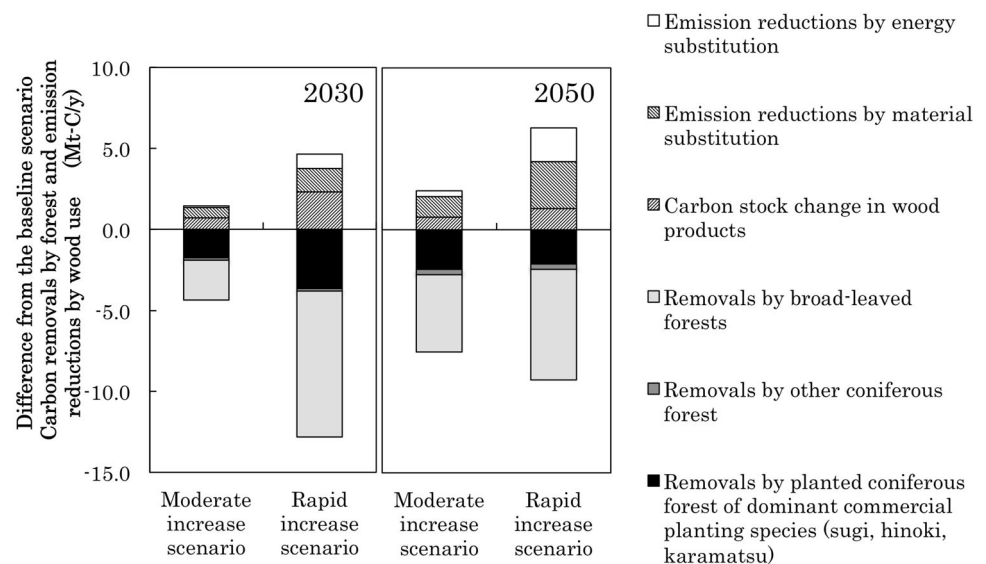


Figure 8 shows a breakdown of the sum total of carbon removal by forests and carbon emission reductions by wood use in 2030 and 2050 under the scenarios. Figure 9 shows their differences from the baseline scenario. The sum totals under the moderate increase scenario and the rapid increase scenario are 75.0 and 85.5 %, respectively, of those for the baseline scenario in 2050. It is also interesting to note that the breakdown ratios change dynamically. Under the baseline scenario, the carbon removal by forests is large, particularly for broadleaved forest. On the other hand, under the rapid increase scenario, the carbon removal by forests was 39.6 % of those under the baseline scenario in 2030, due to increased harvesting. The carbon removal by forests under the rapid increase scenario returned to 51.8 % of the baseline in 2050 by the promotion of replanting and the use of new high-yielding varieties. Under the moderate and the rapid increase scenarios,

the emission reductions due to carbon stock changes in HWP, and material and energy substitution, become larger. The emission reductions under the rapid increase scenario become 76.5 % of carbon removal by forests in 2050. Increases in emission reductions due to wider wood use compensate for a 67.9 % decrease of carbon removal in 2050 under the rapid increase scenario, compared to the baseline, as shown in Fig. 9.

Discussion

The results of the projection are summarized as follows:

1. The carbon removal by forests and the emission reductions by the expanded use of wood vary greatly among the scenarios.

2. Carbon removal by forests will gradually decrease but continue to be positive under all scenarios considered in this study. Forests in Japan will not become a net source of emissions by 2050.
3. The baseline scenario is the most effective for the mitigation of climate change, followed by the moderate increase scenario and the rapid increase scenario, for most periods.
4. The sum total of carbon removal in forests and carbon emission reductions by wood use under the rapid increase scenario is greater than the one under the moderate increase scenario, after 2043.
5. The emission reduction by wood use becomes equal to 76.5 % of the removal by forests under the rapid increase scenario, in 2050.
6. Although carbon removal by forests declines with an increase in harvesting, increases in emission reductions due to wider wood use compensate for 67.9 % of the decrease of removal in 2050, under the rapid increase scenario.
7. The carbon removal by broadleaved forests could be substantial.
8. Substitution of wooden building construction for non-wooden construction could be the most effective mitigation strategy for wood use.

The results of the projection indicate that the baseline scenario is most effective for the mitigation of climate change until 2050. However, determination of which scenario would be the most effective requires consideration not only of climate change mitigation but also factors such as industrial and regional development, as well as the other functions of forests. Lecocq et al. (2011) considered that the stock policy (payment for sequestration in situ) is the best approach for mitigation in France, but this would have negative impacts on consumers.

The period of projection is also significant for the determinations. The results suggested that, in Japan, carbon removal in forests is the most important factor until 2050. Few of the planted forests would be 100 years or older by 2050. Planted forests would be able to remove carbon more effectively until stands age in our 3-PG model than given in conventionally used yield tables. Broadleaved forests showed larger growth with our model than in yield tables, while assumptions on natural regeneration were conservative in our model. The growth rate of forests will decline eventually as they age. On the other hand, emission reductions through wood use will become relatively more important over the extremely long term. Hofer et al. (2007) showed that short-term and long-term carbon dioxide effects can differ significantly in this context, and that focusing forest management on the creation of sinks may

trigger major reductions in carbon dioxide emissions over the short term, but that over the long term, these forests could become carbon dioxide sources during catastrophic events. The results of Hofer et al.'s (2007) projection for Switzerland and the discussion in that study are meaningful to our projection for Japan.

If the period of projection is extended, such as until 2100 or 2200, the results may change because the effect of carbon removal by forests will reduce due to forest aging, and the mitigation effects due to material and energy substitution may become greater over the longer term.

Earlier studies, such as those by Perez-Garcia et al. (2005) and Werner et al. (2005), showed that an increased production of timber for wooden construction to displace non-wooden buildings would be an effective measure for climate change mitigation. On the other hand, Kallio et al. (2013) and other studies have suggested that the harvesting of forests for biomass energy and other short-term uses would not be beneficial for climate change mitigation, at least not for a period of decades. In the scenarios we examined, more harvests and wood use would accompany a higher ratio of wooden construction, as well as greater use of wood for energy and other short-term uses. Moreover, an increase in the harvest might result in a decrease of wood imports if wood consumption does not increase too much. Fewer imports result in less felling abroad, but the effects on overseas forests were not evaluated in our simulation model. Because of the mixture of “substituting uses” with “different carbon emission reduction intensities,” both moderate and rapid increase scenarios were not found to be effective in climate change mitigation for decades of simulation.

Our simulation showed that the best scenario in terms of carbon stock differed between biomass and soil. The soil carbon stock is driven by litter inputs to the soil (natural as well as induced by humans due to harvesting). Forest harvesting increases the amount of human-induced litter input to soil through the roots and unused branches and leaves remaining, while it decreases the amount of natural litter input. Our study indicates the importance of an integrated process-based carbon model, which includes carbon cycles of both biomass and soil (as ours does) to simulate the total carbon budget of forests.

To ensure the robustness of the results of our simulation, the accuracy of the parameters of the forest sector carbon integrated model, and the sensitivity of the simulation results, should be verified. Carbon removal from both natural and planted forests may be increasingly difficult to ascertain when the forests are older than in the current age structure. Because 79 % of the planted forests were between 26 and 60 years old in 2012 in Japan, the majority of them will be 65–100 years old in 2050. Further research is required to verify these results.

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